Is binary sequential decay compatible with the fragmentation of nuclei at high energy ?

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Abstract

We use a binary sequential decay model in order to describe the fragmentation of a nucleus induced by the high energy collisions of protons with Au nuclei. Overall agreement between measured and calculated physical observables is obtained. We evaluate and analyse the decay times obtained with two different parametrisations of the decay rates and discuss the applicability of the model to high energy fragmentation.

PACS : 25.40.-h 25.70.Pq 05.90+m

Key words : Nucleon-nucleus reaction. Fragmentation. Sequential decay. Intermediate mass fragment yields. Reaction time.

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The time evolution of a nuclear system which undergoes fragmentation is still an open question. It is, of course, strongly correlated to the dynamical evolution of the process. Hence, time arguments may help to differentiate between various mechanisms. Experimental quantities sensitive to the evolution are of great interest. The aim of the present study is an attempt to test a simple model describing sequential decay by working out specific observables which can be confronted with available experimental results. Characteristic times given by the model are compared to experimental and theoretical estimates. This work complements a recent analogous study in which simultaneous decay has been investigated [1].

The experiment concerns the fragmentation produced by the impinging of a proton on a Au target at 8.1 GeV incident energy. After the fast cascade process a system with mass A $\simeq$ 160 is left over. This sytem decays into fragments and has been investigated experimentally [2].

Among many different fragmentation mechanisms the disassembly through sequential binary decay has been worked out in different forms [3, 4, 5]. Here we introduce a time-dependent description which has been proposed some time ago [6]. We start with an excited system (here A$\simeq$ 160) which decays into smaller species by means of a binary sequential decay process. The binary decay is governed by transition rates, either taken from the Weisskopf (WTR) detailed-balance principle [7] or from the transition-state theory (STR) proposed by Swiatecki [8]. The process is numerically simulated as discussed in [6]. At each time step, any composite fragment which has been formed can decay into two smaller species corresponding to a decay channel determined by means of a random procedure. The fragments fly apart in a randomly chosen direction due to the Coulomb repulsion which acts between them, in such a way that they never overlap in space. The process stops when all the generated species can no longer disassemble because their energy lies below the lowest decay threshold. The difference between the present calculation and the original one [6] consists of the introduction of the Coulomb interaction which acts between all fragments at any time. As time flows these fragments fly apart along classical trajectories. The simulation is repeated in order to get significant statistics.

We have applied the model to the calculation of different observables by choosing an initial excitation energy $E/A = 5\ MeV$ which lies in the range

of the expected experimental excitation energies. Calculations have been made for $E/A = 4\ MeV$ and the results are not significantly different. In the sequel we concentrate on the case where $E/A = 5\ MeV$ for which the intermediate mass fragment (IMF, i.e. $3 \leq Z \leq 20$) multiplicity is closest to the experimental value. Fig. 1a shows the charge distribution obtained with the two types of transition rates. Both calculations show qualitative agreement with the experiment. Fig. 1b concerns the energy distribution of C isotopes. For energies of the carbons lower than 60 MeV, the calculated yields follow nicely the experimental ones. Discrepancy with the experiment appears for higher carbon energies. The measured high energy tail of the distribution cannot be reproduced by the models. We shall come back to this point in the sequel. A second observable is shown in Figs. 2, where we compare the energy distribution of C isotopes for different multiplicities M_{IMF} of intermediate mass fragments. The evolution of the calculated spectra with the multiplicity looks similar to the experimental ones. One has to keep in mind that M_{IMF} in the lower part is the total M_{IMF} while in the upper part M_{A} is the number of measured IMF's which is of course smaller than M_{IMF} due to detector efficiency. In particular, the model reproduces the shift to the left of the maxima of the curves with increasing IMF multiplicity. This shift can be qualitatively understood as being due to the fact that the energy which is available for the emitted carbon diminishes with the generation of an increasing number of IMF's which take up part of the total conserved energy. More details about these distributions can be seen in Figs. 3. Comparing Figs. 3a and 3b one observes that the energies of the maxima agree quite nicely. As for the mean energies, the experimental values are rather constant while the calculated ones decrease substantially with M_{IMF} when one uses WTR rates. This may arise from the fact that in the experiment various excitation energies are involved and hence, in the experimental curves, both the maxima and the slopes are changing. The results obtained with the MMMC [9] and the SMM [10] models are shown in Figs. 3c and 3d respectively. As it can be seen MMMC simulations lead to rather constant mean energies, although their absolute values are somewhat smaller than the experimental ones. The SMM simulations show to some extent the decreasing trend of the sequential decay model. If one knows that the SMM allows for the existence of a final stage which does not appear in MMMC calculations and in which the system evaporates particles from the existing excited fragments, it may be tempting to believe that the trend observed in these mean energies could be related to the sequential character

of the disassembly. The calculations with STR which are not shown behave similarly, the mean values being closer to those shown in Fig. 3c.

From the present results, one would conclude that the present model works quite satisfactorily. This has also been observed in the application of the model to other sytems [11]. One observes however some discrepancies such as the behaviour of the high energy tail of the carbon energy spectrum already mentionned above and shown in Fig. 1b. This may be due to the sequential character of the process. The C fragments are generated at a later stage in the decay chain in both calculations. The kinetic energies they acquire are governed by Coulomb barriers which are not high enough for these kinetic energies to reach the values observed in the experimental tail of the distribution.

As already stated above, time is certainly correlated to the characteristic features of the fragmentation process. It is, of course, possible to estimate the duration of the decay. In Figs. 4 we present the time evolution of the cumulated particle and fragments yields. These figures show two interesting facts. The WTR rates lead more quickly than the STR rates to the generation of light particles and fragments, but after some time STR distributions start growing, "catch up" with and even overshoot the WTR ones in the case of IMF generation. The STR scenario corresponds to a generalized fission process which, at least at the beginning of the decay, is slower than light particle evaporation.

The second interesting and important fact concerns the duration time of the process. An estimate of this time can be read from Figs. 4 for both WTR and STR rates. When STR rates are used the generation of light species Z=1 (resp. Z=3) is of the order of 10^4 - 2 $\times 10^4$ fm/c (resp. 10^4 fm/c). The IMF generation takes also about 10^4 fm/c. However, measured fragment correlations [12] indicate that the characteristic correlation time is approximately 80 fm/c or shorter. This strongly disagrees with the STR results.

If the process is governed by WTR rates, the light species generation is of the order of 5 $\times 10^3$ to 10^4 fm/c for Z=1 and 5 $\times 10^2$ fm/c for Z=3. Most of the intermediate mass fragments are already generated after a time interval which does not exceed 300 fm/c. Hence the time over which IMF's are created is rather short, approximately three times larger than the experimentally

estimated time. But one should notice that the WTR rates may not be very realistic for high excitation energies, see ref. [13].

The results obtained above show that STR rates generate a process which is rather slow and for WTR rates the time scale is much shorter, although both merge to similar final fragment size distributions as already mentionned above.

Whatever the degree of validity of the transition rates used in the present analysis, the shortness of the estimated experimental fragmentation time ($\simeq 80$ fm/c) raises the question of the validity of the mechanism itself. Each decay of a given fragment into two new fragments is treated independently of the rest of the system in which this binary process occurs, except for the conservation of total energy. This is conceptually difficult to believe if the process is so quick and the description of the process introduced by means of the WTR rates becomes doubtful. In this case multiparticle correlations between fragments interacting through their mutual Coulomb interaction are certainly strong, and the barriers and decay rates cannot be treated independently. Hence the quick decay must be governed by another mechanism.

In summary, the present binary decay model using WTR and STR decay rates reproduces well the experimental charge and energy distributions obtained for p + Au collisions at 8.1 GeV. As for the crucial observable, the time scale, it fails when one uses STR rates. In the case of WTR rates, the time scale is not too far from the experimentally estimated time but the validity of the mechanism itself is questionable.

Acknowledgments

The authors would like to thank S.P. Avdeyev for his kind help and interesting suggestions. They are grateful to D. Gross for a critical reading of the text and constructive comments.

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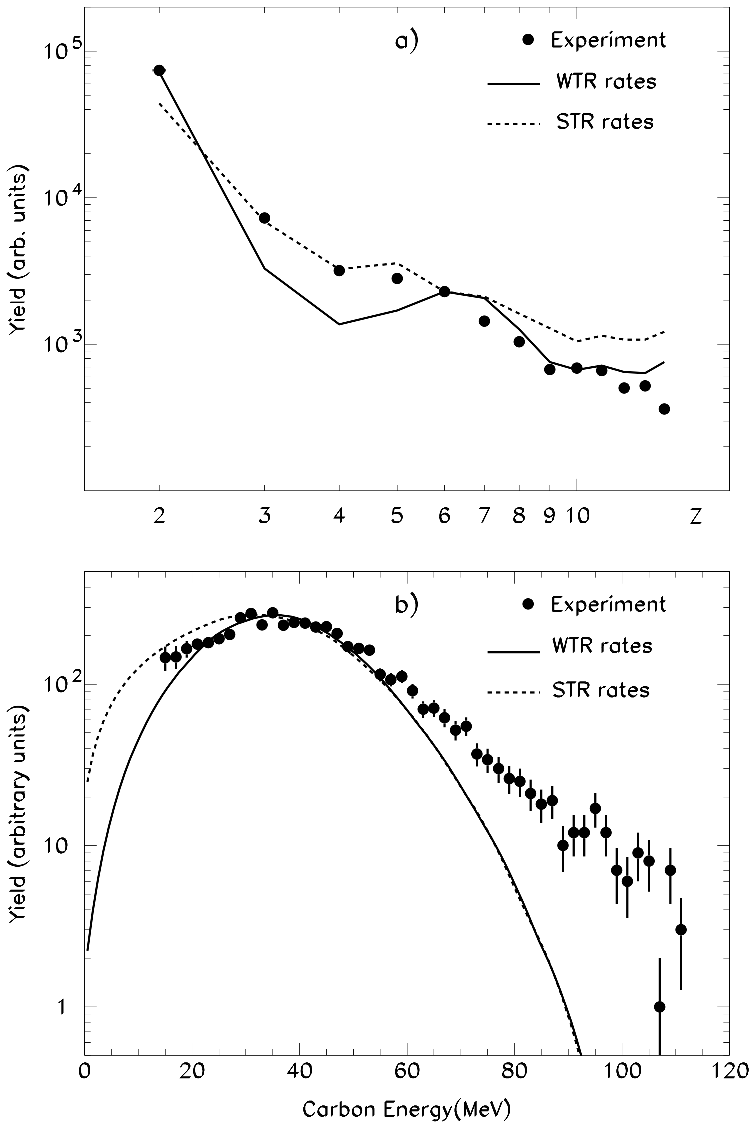

Fig. 1 : (a) : Charge distribution of fragments; (b) : energy distributions of carbon isotopes.

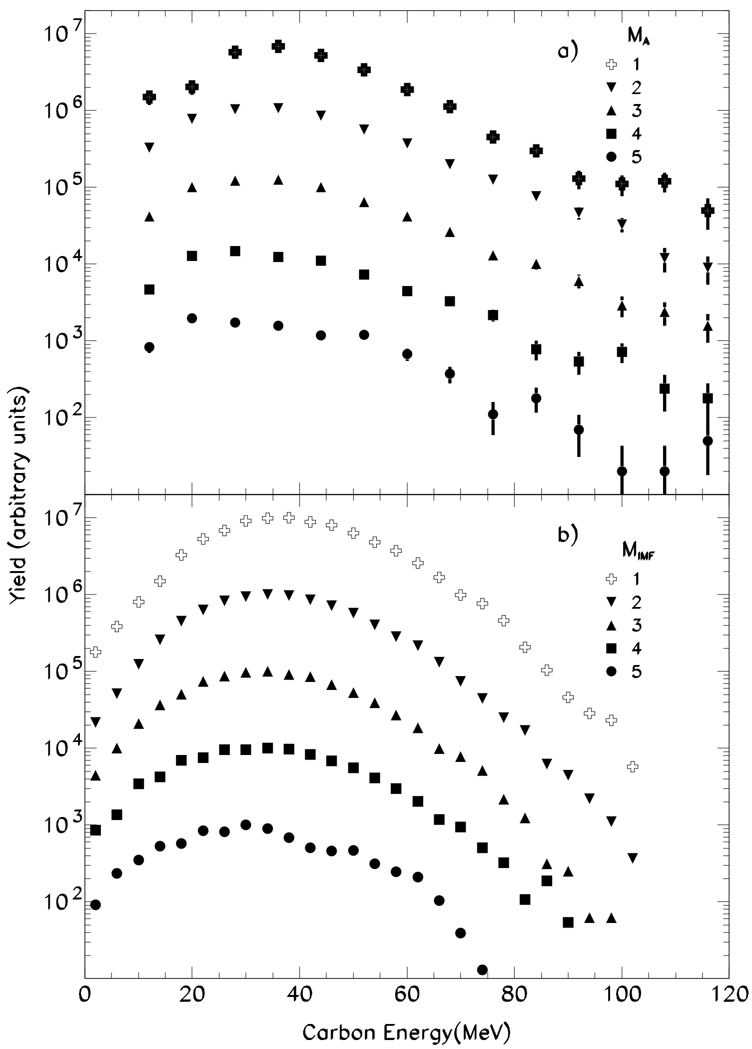

Fig. 2 : Yield of carbon isotopes as a function of energy for different intermediate mass fragments multiplicities (M_{IMF}). (a) : experiment (M_A is the number of measured IMF's); (b) : calculation with WTR rates. Results obtained with STR rates are not shown but very close.

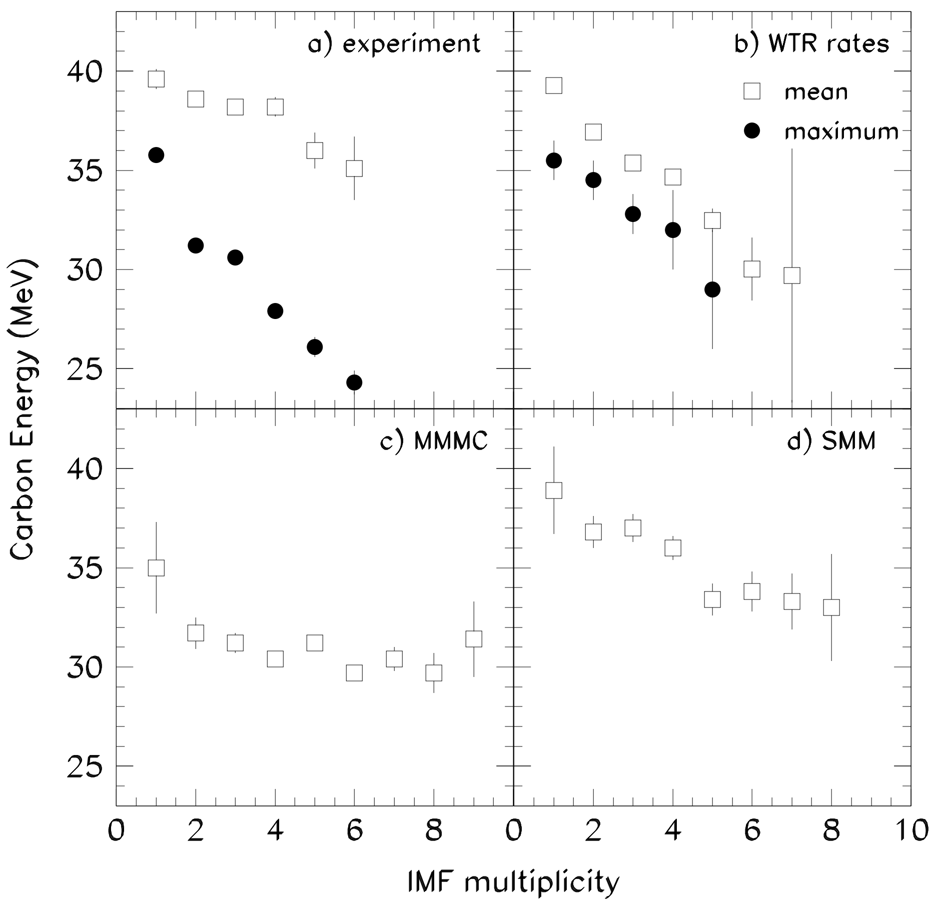

Fig. 3 : Mean and maximum of the energy distribution of carbon isotopes as a function of the multiplicity of intermediate mass fragments (M_{IMF}) : (a) : Experiment; (b) : calculation with WTR rates for excitation energies of 5 MeV/nucleon; (c) : mean energy obtained with the MMMC model [9] for 5 MeV/nucleon; (d) : mean energy obtained with the SMM model [10] for 5 MeV/nucleon. E_{mean} is defined as the average value obtained by integration over the energy distribution of the carbons.

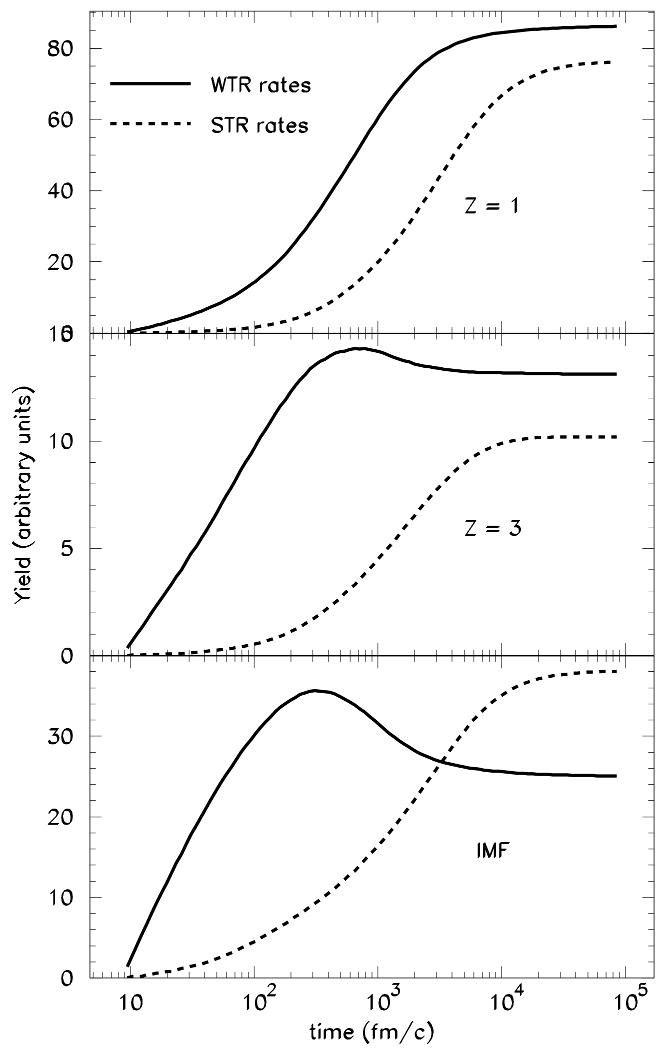

Fig. 4 : Time dependence of the yields of particles and fragments present in the system during the binary sequential decay process for WTR and STR rates.